Fermilab

SOIL ACTIVATION CALCULATIONS FOR

THE ANTI-PROTON TARGET AREA

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ABSTRACT.

This is a summary of the soil radioactivation calculations performed by Craig Moore and myself. The annual quantities of ^3H and ^{22}Na produced in the soil surrounding the $\bar{p}$ target station and the quantities of those radionuclides reading the Silurian aquifer each year are calculated for the construction design of the $\bar{p}$ target station and a particular set of anticipated operating parameters.

I. Geometry

A possible design of the $\bar{p}$ production target and collecting system of magnets is shown in Figure 1.[1] The beam is pitched vertically downward at 10 mrad onto the tungsten target. The C-magnet starts to separate the secondaries by charge and momentum. The quads focus the particles of the desired momentum onto a trajectory through the hole in the dump while off-momentum secondaries are lost on the dump. Since these magnets provide a significant part of the shielding, any major changes in their dimensions may have a major effect on the calculated radionuclide production, and should therefore be checked by an additional calculation.

The shielding around the target area consists of a combination of earth, steel, and dense aggregate concrete (iron ore plus cement mixed on-site). An impermeable membrane ("bathtub") and a series of underdrains serve to collect the water containing most of the leached radionuclides.

To reduce costs, the steel and dense aggregate shielding are placed only where needed - from z=0 to 10.7m and from z=19.8 to 22.9m.[2] (All distances are measured from the target). In those regions in which this shielding is not used, soil is used instead. A cross section of the target tunnel and underground shielding is shown in Figure 2.

This figure also shows the water collection assumptions used in the calculation. All radionuclides originating above the bathtub, or in the gravel backfill below the bathtub but above the center of the secondary underdrain are assumed to be collected for disposal as radioactive waste. Thus for environmental protection purposes we need only be concerned about those radionuclides produced-the regions labelled "unprotected soil."

II Radionuclide Production

The total number of atoms of each radionuclide which are produced in the unprotected soil may be written as the product

$$N_i = F\ P\ S\ K_i \tag{1}$$

where

F = intensity of beam on target (protons/pulse)

P = number of pulses per year on target

S = number of "stars" (hadron-nucleus interactions) produced in unprotected soil per incident proton

K_i = probability that an atom of the i-th radionuclide will be produced at each "star"

We take $F = 10^{13}$ protons/pulse, and a one-second cycle time during operation.[1]

Assuming that the accelerator will operate 44 out of every 52 weeks, that each week will consist of 120 hours of actual operation, and that antiproton physics will be run for 1/4 of the total physics program[3], we have

$$P = \frac{44}{52} \times \frac{120}{168} \times 0.25 \times 3.2 \times 10^7 \text{sec/yr} = 0.15 \times 3.2 \times 10^7 = 4.8 \times 10^6 \text{ pulses/year.}$$

The star production in unprotected soil was calculated for the geometry shown in Figs. 1 and 2 and the materials specified in Table 1 using the Monte Carlo program CASIM.[4] For ease in understanding the weaknesses of the shielding, the stars produced in unprotected soil were totalled separately for the region below the target hall, the regions on either side of the hall, and the regions below each lower corner of the enclosure. (These are the regions labelled "bottom", "side", and "corner" on Fig. 2.) Thus values of S_j for three separate regions are calculated.

TABLE 1

DENSITIES AND INTERACTION LENGTHS
OF THE MATERIALS USED IN THE
CASIM CALCULATION OF STAR PRODUCTION

Casim Material Code	Material	Object	Density	Interaction Length
0	Vacuum		0	∞
1	Tungsten	Target	19.3 g/cm^3	9.9 cm
2	Concrete	Walls	2.4	44.6
3	Soil	Soil	2.0	53.6
4	Iron	Magnets, dumps, etc.	7.86	17.3
5	Dense Aggregate Shielding	Side Shield	3.20	41.5

Because of the large attenuation of the insoluble steel and dense aggregate shield, a fair amount of computer time was required to get reasonable statistics for the quantities S_j. Five runs of 10^5 stars each had their parameters chosen in an attempt to separate the random effects of statistical fluctuations from the possible systematic effects of the wide angle biassing used to give improved statistics at large radii. The results of these CASIM runs are given in Table 2.

TABLE 2

RESULTS OF CASIM RUNS FOR STARS IN UNPROTECTED SOIL (S_j)

FOR THE SIDE, CORNER AND BOTTOM REGIONS SHOWN

IN FIGURE 2

THE UNITS ARE 10^{-4} STARS/INCIDENT PROTON

Wide Angle Biassing	Seed for Random Number Generator 382515531	Seed for Random Number Generator 740717077
None	Side: 6.7 Corner: 24 Bottom: 2.8 Total 34.	Side: 8.0 Corner: 10. Bottom: 12. Total 30.
Medium	Side: 13. Corner: 11. Botton: 4.6 Total 29.	Not Run
Strong	Side: 5.4 Corner: 7.2 Bottom 33. Total 45.	Side: 6.0 Corner: 6.6 Bottom: 3.9 Total 16.5

These runs may be considered to be independent estimates of the same quantities. Two runs with the same random number generator seeds are derived from different sequences of random numbers, and hence are totally independent statistically. Those runs which share the same seed but use different degrees of biassing are correlated in the sense that the same sequence of random numbers is followed in the calculations every time a new incident particle is introduced.[5] However, since the various secondary particles are selected from different distributions in the two (or three) cases, the results have a certain amount of statistical independence. To confirm this, merely note that a different region (side, corner, or bottom) had the greatest number of stars in each run within a set of correlated runs.

I consider these as equally valid independent measurements, and take their means and standard deviations. These are shown in Table 3. Note that the error quoted is a measure only of the statistical uncertainty involved in the calculation, and does not indicate the uncertainty caused by our lack of knowledge of the physics involved. A rough estimate is that this uncertainty amounts to not more than a factor of three either way.

TABLE 3

S_j STARS PRODUCED IN UNPROTECTED SOIL AROUND THE

$\bar{p}$ TARGET ENCLOSURE, PER INCIDENT PROTON.

ERRORS SHOWN ARE STATISTICAL ONLY

Region	Sj, Stars Produced Per Incident Proton
Side	$(7.8 \pm 1.5) \times 10^{-4}$
Corner	11.8 ± 3.5
Bottom	11.3 ± 6.3
Total	$(30.7 \pm 5.1) \times 10^{-4}$

It has been shown that the most important radionuclides in situations involving groundwater contamination are tritium (^3H) and ^{22}Na.[6,11] In comparison with these, all other radionuclides may be neglected either because their production cross sections are much smaller, or because their lifetimes are too short to allow any appreciable quantities to reach the aquifer.

In the most detailed calculation on this subject, M. Awschalom[9] used a calculated value of Σ_{22} = 1.2 x 10^{20} barns = 1.2 x 10^{-4} cm^2 for the macroscopic cross section for ^{22}Na production in glacial till. This calculation was based on the chemical analysis of the till sample and on A. Van Ginneken's compilation of ^{22}Na production cross sections. When divided by the non-elastic cross section for the same mixture (Σ_{ne} = 1.1 x 10^{-2} cm^2/gm), this yields the often quoted value of

$$K_{22} = \frac{\Sigma_{22}}{\Sigma ne} = \frac{1.2 \times 10^{-4} cm^2/gm}{1.1 \times 10^{-2} cm^2/gm} = 0.011$$

atoms of ^{22}Na per star.

Subsequent measurements by Borak et al.[10,11] for various clays and glacial till yielded values of Σ_{22} from 1.6 to 2.3 x 10^{-4} cm^2/gm. At least part of the difference between this value and the one calculated by Awschalom can be explained by differences between the assumed and actual chemical composition of the till, by differences in the energy thresholds used in calculating the hadron flux, and by uncertainties in the incident spectrum in the measurements of Borak et al.

Using the value of Σ_{22} = 2.1 x 10^{-4} cm^2/gm measured for glacial till, we obtain the value

$$K_{22} = 0.02$$

Using the measured value for leachable tritium (total tritium could not be measured) produced in glacial till of

$$\Sigma_3 = 8.2\text{x}10^{-4}\ \text{cm}^2/\text{gm}$$

we find

$$K_3 = \frac{\Sigma_3}{\Sigma_{ne}} = \frac{8.2\text{x}10^{-4}\ \text{cm}^2/\text{gm}}{1.1\text{x}10^{-2}\ \text{cm}^2/\text{gm}} = 0.075$$

leachable atoms of ^{3}H per star.

The total annual production of these radionuclides is given (in atoms/year) by Eq'n 1. The annual production of the i$^{\text{th}}$ radionuclide in region j (side, corner, bottom) is given, in the more convenient units of curies per year, by

$$N_{ij} = \frac{F\ P\ S_j\ K_i}{\tau_i \cdot 3.7\text{x}10^{10}} \qquad (1')$$

Here τ is the mean life, or $\tau = t_{\frac{1}{2}}/\ln 2 = 1.44\ t_{\frac{1}{2}}$.

We now have the following parameters which may be used to calculate the annual radionuclide production, N_{ij}, of the i-th nuclide in region j:

$F = 10^{13}$ protons/sec
$P = 4.8\text{x}10^6$ pulses/year
$K_3 = 0.075$ atoms of ^{3}H per star
$K_{22} = 0.02$ atoms of ^{22}Na per star
$\tau_3 = 1.44\text{x}12.3$ yrs $= 17.7$ yrs $= 5.5\text{x}10^8$ sec
$\tau_{22} = 1.44\text{x}2.6$ yrs $= 3.75$ yrs $= 1.2\text{x}10^8$ sec

Insertion of these values and the annual star production S_j from Table 3 into equation 1' yields the radionuclide production given in Table 4.

TABLE 4

Annual Radionuclide Production Around $\overline{p}$ Target Area, N_{ij}

	i = ^{3}H (Leachable)	^{22}Na (Total)
j = Side	0.14 mCi	0.17 mCi
Corner	0.21	0.26
Bottom	0.20	0.24
Total	0.55 mCi	0.67 mCi

III. Leaching of Radionuclides

The work of Borak[11] et al. has shown that 10-20% of the ^{22}Na is immediately leached out of the clay, and that subsequently very little additional ^{22}Na is leached. The quantities of ^{22}Na which are leached from unprotected soil are therefore taken as 15% of the corresponding values of Table 4.

These authors were only able to measure the cross section for producing leachable tritium. Hence this cross section was used above, and all of the tritium so produced is considered to be leachable.

IV. Vertical Transport to Silurian Aquifer

The precise vertical water velocity through the glacial til in the area of the $\bar{p}$ target station is not yet known. The most reliable estimates[13] are in the range of 3.6 to 7.2 feet/yr. To be conservative, the latter value will be used until a more precise figure is available. Since the horizontal velocities in the aquifer are many feet per day, decay in transit to the site boundary will be neglected.

Because of ion-exchange mechanisms, the various ions transported through the clay do not necessarily migrate at the same velocity as the water carrying them. Measurements indicate that the tritium does move at essentially the same speed as the water, while the ^{22}Na moves with a velocity of only 0.44 that of the water.[11]

The quantity of the i-th radionuclide which is produced in the j-th region, and is then leached and transported to the aquifer while decaying en route is

$$m = N_{ij} f_i \exp\left(- \frac{E_j - E_a}{V_i \tau_i}\right)$$

where

f_i is the fraction leached:

$f_3 = 1.0$

$f_{22} = 0.2$

E_j is the elevation of region j:

$E_s = 727'$

$E_c = 720'$

$E_b = 716'$

E_a is the elevation of the top of the aquifer, $E_a = 677'$

V_i is the vertical velocity of nuclide i:

$V_3 = V_w = 7.2$ ft/yr

$V_{22} = 0.44\ V_w = 3.2$ ft/yr

The quantities M_{ij} and the sum $M_i = \Sigma_j\, m_{ij}$ over all three regions are given in Table 5.

TABLE 5

Annual production from each region which reaches the aquifer, m_{ij}, and total for each radionuclide of interest, M_i.

	$i = {}^3H$	^{22}Na
j = side	.095 mCi	0.39 μCi
corner	.15	1.05
bottom	.15	1.35
total	0.39 mCi	2.8 μCi

To put these numbers in perspective let us make the somewhat extreme assumption that all the activity reading the aquifer happens to flow into a single well used by only one person. This person uses 40 gallons of water a day from the well. The concentration of these radionuclides in the well water is given by

$$C_i = M_i/(40 \text{ gal} \times 3.8 \text{ } \ell/\text{gal} \times 365 \text{ days/yr})$$

then

$$C_3 = 7.1 \text{ nCi}/\ell = 7.1 \text{ pCi/m}\ell$$

$$C_{22} = 50 \text{ pCi}/\ell = 0.050 \text{ pCi/m}\ell$$

The most stringent limits on radioactivity in water are those of the Encironmental Protection Administration. Their limits for ^{3}H and ^{22}Na in drinking water supplies (each in the absence of all other radionuclides) are

$$L_3 = 20 \text{ pCi/m}\ell$$

$$L_{22} = 0.2 \text{ pCi/m}\ell$$

With a mixture of radionuclides, the weighted sum $\Sigma \frac{C_i}{L_i}$ must be less than 1. For the present case,

$$\Sigma \frac{C_i}{L_i} = \frac{7.1}{20} + \frac{0.050}{0.2} = 0.61$$

Thus for the assumptions given here (some of which are rather extreme), the concentration of radioactive nuclides in the groundwater will be below all present Federal limits.

V. Acknowledgement:

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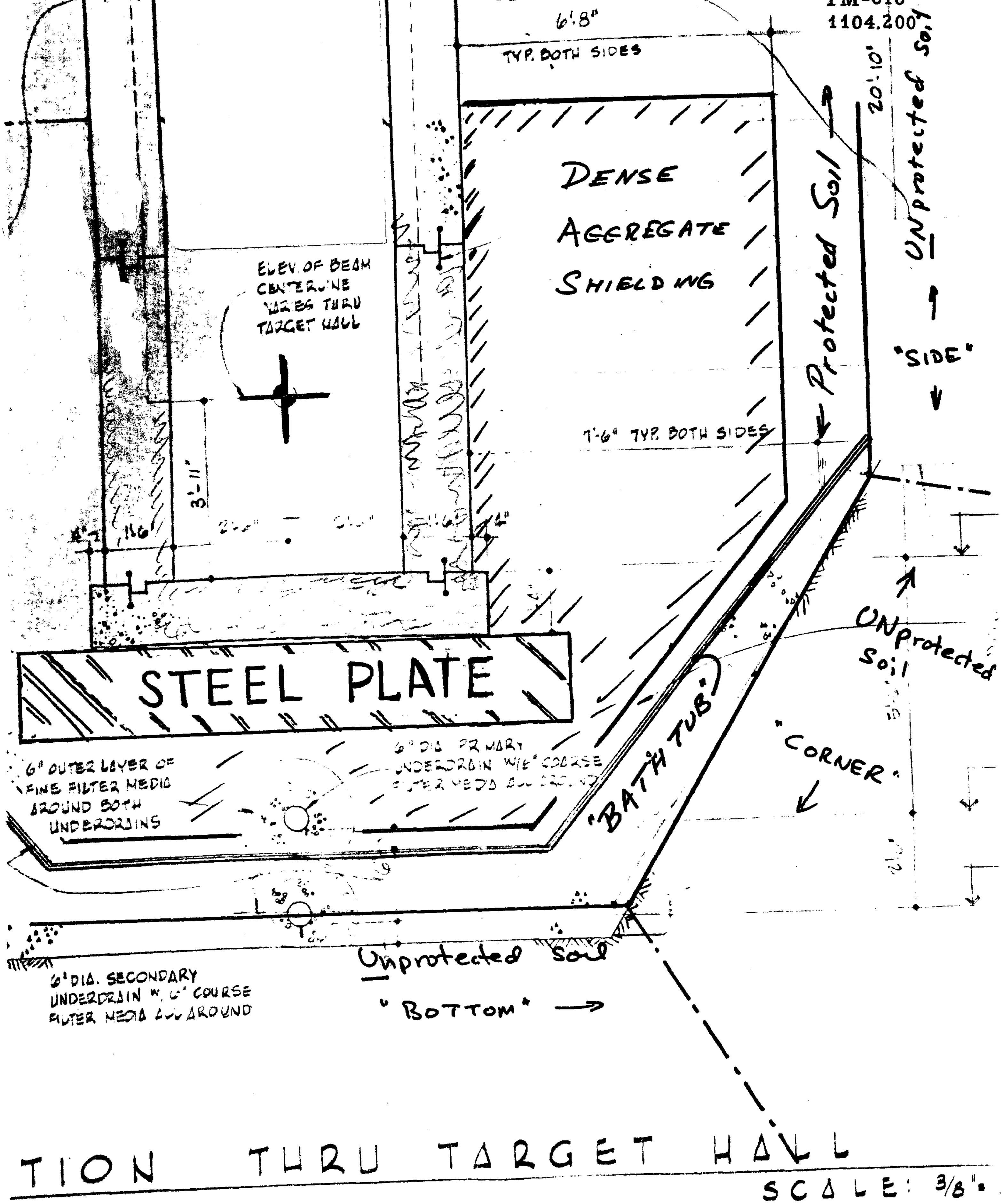

Figure 2. Cross-section through target enclosure and underground shielding.

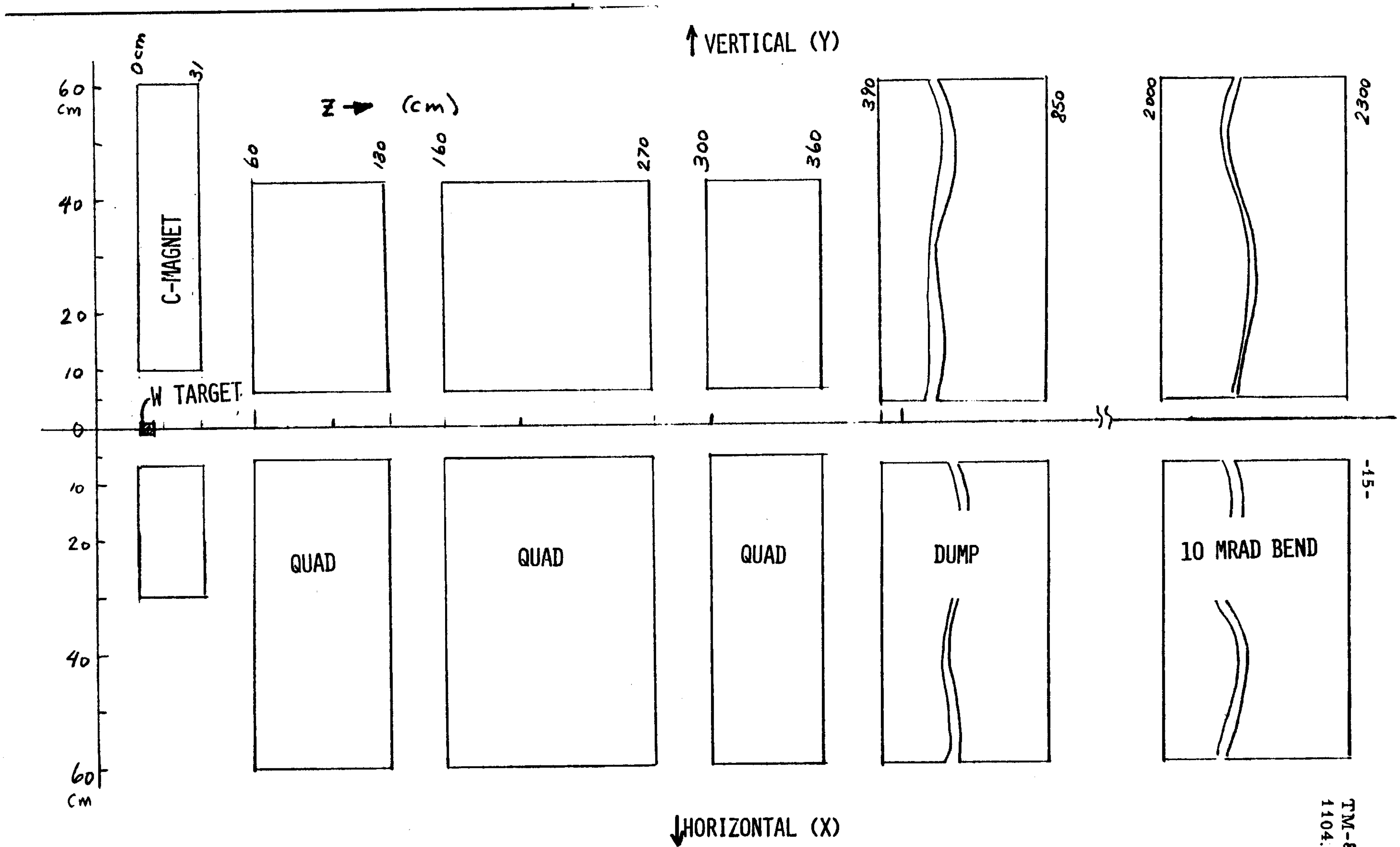

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Figure 1. A possible target system for $\overline{p}$ production. This geometry was used for the calculation.